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# Virtual Reality-Based Dichoptic Therapy for Childhood Amblyopia: A Narrative Review

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## Abstract

**Background:** Amblyopia commonly referred to as 'lazy eye' affects an estimated 1%–5% of children worldwide, making it the most prevalent cause of preventable monocular visual impairment in the pediatric population. Conventional treatments, including occlusion therapy (patching) and atropine penalization, improve monocular visual acuity (VA) by suppressing input from the fellow eye; however, they are beset by poor patient adherence, psychological burden, and the persistent failure to rehabilitate binocular visual function and stereoacuity.

**Methods:** A comprehensive narrative review was performed using systematic searches of PubMed, Embase, the Cochrane Library, and Web of Science, covering peer-reviewed publications from 2020 to 2026. Search terms included amblyopia, dichoptic therapy, virtual reality, binocular treatment, lazy eye, VR headset, Luminopia, and CureSight. Randomized controlled trials (RCTs), systematic reviews, meta-analyses, pilot studies, and prospective cohort studies evaluating VR-based dichoptic interventions in children with amblyopia were included.

**Results:** The evidence base encompasses two U.S. Food and Drug Administration (FDA)-cleared dichoptic devices Luminopia (VR headset) and CureSight (eye-tracking-based dichoptic system) alongside multiple investigational platforms. Pivotal RCTs demonstrated non-inferiority of dichoptic VR therapy to conventional patching in improving amblyopic eye VA, with improvements ranging from 0.28 to 1.32 logMAR lines over 10–16 weeks. Dichoptic VR therapy conferred superior stereoacuity outcomes, with significant reductions in stereoscopic thresholds compared with monocular suppression-based approaches. Treatment adherence exceeded 80%–91% in multiple studies, substantially surpassing patching compliance rates. Adverse events were

predominantly mild and transient, including cybersickness and temporary diplopia. Systematic reviews and meta-analyses confirm the overall efficacy of dichoptic therapy as a non-inferior to equivalent alternative to patching, with a statistically significant small advantage over patching reported in the most recent meta-analysis (mean difference 0.02 logMAR; 95% CI: 0.00–0.04).

**Conclusions:** VR-based dichoptic therapy constitutes a scientifically grounded, patient-centered, and increasingly evidence-supported treatment paradigm for childhood amblyopia. Its capacity to simultaneously improve VA, stereo acuity, and binocular function while offering superior adherence and reduced psychosocial burden positions it as a compelling alternative or adjunct to conventional therapy. Future research priorities include standardized treatment protocols, long-term durability data, integration of adaptive artificial intelligence algorithms, and comparative effectiveness studies across amblyopia subtypes and age groups.

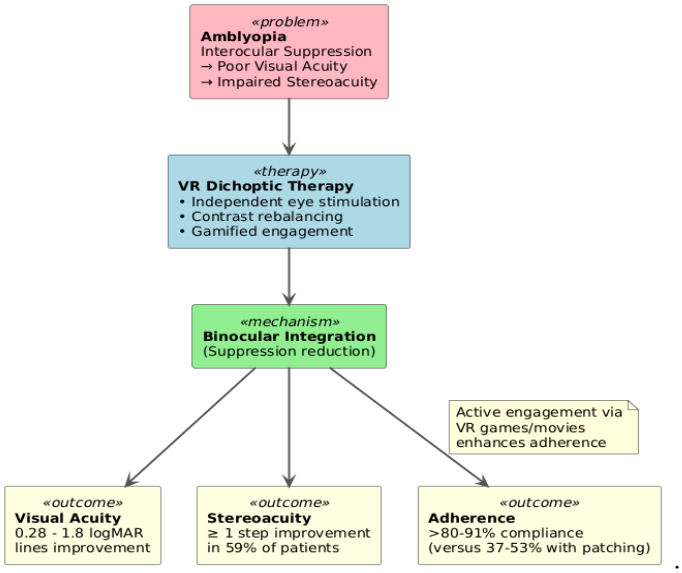


***Fig 1: Graphical Abstract***

## INTRODUCTION

Amblyopia is a neurodevelopmental disorder of the visual cortex arising from aberrant binocular visual experience during the critical period of visual development typically the first decade of life. Characterized by unilateral (and, less commonly, bilateral) reduction in best-corrected visual acuity (BCVA) that cannot be

attributed to structural ocular pathology, amblyopia represents the most common cause of preventable monocular vision loss in childhood, affecting approximately 1%–5% of the global pediatric population (Hu et al., 2022; Janti et al., 2024). A landmark meta-analysis of 60 population-based studies encompassing over 1.8 million subjects estimated a pooled global prevalence of 1.44% (95% CI: 1.17%–1.78%), translating to tens of millions of affected individuals worldwide (Hashemi et al., 2019). In the United States alone, the condition is estimated to affect 2%–4% of children, representing a substantial public health burden with implications for educational performance, occupational opportunities, and long-term quality of life (American Academy of Ophthalmology, 2024). The pathophysiological substrate of amblyopia involves disruption of the normal binocular cortical experience during the critical period, leading to suppression of the amblyopic eye's input at the level of the primary visual cortex and higher visual processing areas. This interocular suppression characterized by the dominant fellow eye actively inhibiting signals from the amblyopic eye results not only in reduced VA but also in deficits of contrast sensitivity, spatial distortion, positional uncertainty, and, critically, stereoacuity (Li et al., 2011; Thompson et al., 2024). The three principal etiological subtypes anisometropic (refractive), strabismic, and deprivation amblyopia share the final common pathway of aberrant interocular competition during sensitive developmental windows. The historical gold standard of amblyopia treatment has been monocular occlusion therapy: patching of the fellow (non-amblyopic) eye for several hours per day to force the visual system to process information through the amblyopic eye. While this approach reliably improves VA in compliant patients particularly when initiated before age seven it carries significant limitations. Patching fails to address the binocular dysfunction underlying amblyopia, addresses only monocular suppression rather than its root neural cause, and is associated with poor patient adherence due to discomfort, social stigma, skin irritation, and the psychological burden imposed on young children (Papageorgiou et al., 2019; Wirawan & Setiani, 2023). Atropine penalization of the fellow eye represents an alternative, but similarly suffers from incomplete binocular restoration and occasional accommodation-related side effects. The past two decades have witnessed a paradigm shift in the conceptualization and treatment of amblyopia, driven by converging evidence from visual neuroscience, perceptual learning research, and digital therapeutics. The recognition that interocular suppression rather than simple monocular deprivation is the dominant mechanism underlying amblyopia impairment has catalyzed the development of dichoptic treatment approaches (Hess & Thompson, 2015). Dichoptic therapy involves the simultaneous, independent presentation of distinct visual stimuli to each eye under carefully controlled interocular contrast conditions, with the aim of reducing suppression and restoring binocular integration. Virtual reality (VR) technology, with its capacity for precise, immersive, binocularly differentiated visual stimulation, has emerged as the ideal delivery platform for dichoptic therapeutic paradigms. Two VR-based dichoptic devices have received FDA clearance to date: Luminopia, a VR headset delivering contrast-modulated video content dichoptically, approved for children aged 4–12 years with anisometropic and/or mild strabismic amblyopia; and CureSight, an eye-tracking-based dichoptic system utilizing anaglyph glasses and real-time gaze tracking. Multiple additional VR platforms including

Vivid Vision, NEIVATECH, and investigational game-based systems are under active clinical evaluation globally (Xiao et al., 2022; Wygnanski-Jaffe et al., 2023).

The present narrative review aims to synthesize the current evidence on VR-based dichoptic therapy for childhood amblyopia, encompassing the pathophysiological rationale, technical mechanisms of VR delivery systems, clinical evidence from landmark RCTs and systematic reviews, safety profile, adherence characteristics, and future research directions. By providing a comprehensive appraisal of the evolving evidence base, this review seeks to inform clinicians, researchers, and policymakers regarding the integration of VR-based dichoptic therapy into contemporary amblyopia management paradigms.

## LITERATURE SEARCH STRATEGY

A narrative review methodology was employed to synthesize published evidence on VR-based dichoptic therapy for childhood amblyopia. Comprehensive searches were conducted across PubMed/MEDLINE, Embase, the Cochrane Central Register of Controlled Trials, and Web of Science, spanning publications from January 2010 to June 2025. The search strategy utilized combinations of the following Medical Subject Headings (MeSH) and free-text terms: 'amblyopia,' 'lazy eye,' 'dichoptic therapy,' 'dichoptic stimulation,' 'virtual reality,' 'VR headset,' 'binocular treatment,' 'head-mounted display,' 'perceptual learning,' 'interocular suppression,' 'Luminopia,' 'CureSight,' 'Vivid Vision,' 'NEIVATECH,' 'gamification,' and 'digital therapeutics.' Boolean operators (AND/OR) were applied to maximize retrieval sensitivity and specificity. Inclusion criteria comprised: (a) peer-reviewed original research articles, systematic reviews, meta-analyses, or narrative reviews published in English; (b) studies involving children aged 3–18 years with a diagnosis of amblyopia of any subtype; (c) interventions involving VR-based or dichoptic digital therapeutic approaches; and (d) outcome data including VA, stereoacuity, binocular function, adherence, or safety. Studies focusing exclusively on adult populations or non-VR perceptual learning paradigms were excluded, as were case reports with fewer than five participants. Additional relevant articles were identified through manual reference list screening and citation tracking of included studies. A total of 47 studies formed the primary evidence base for this review, complemented by clinical trial registries and regulatory documentation for FDA-cleared devices.

## PATHOPHYSIOLOGY AND CLASSIFICATION OF AMBLYOPIA

Amblyopia is fundamentally a disorder of cortical visual development rather than a structural or optical defect of the eye itself. During the sensitive period of visual development extending from birth through approximately the first decade of life, with a peak period of maximum plasticity between ages 18 months and 5 years the visual cortex undergoes extensive synaptic reorganization in response to visual input quality and ocular dominance competition. Disruption of this process by unequal or degraded binocular input leads to the establishment of pathological cortical circuits characterized by abnormal interocular dominance and suppression (Thompson et al., 2024). The primary neural mechanism underlying unilateral amblyopia involves interocular suppression at the level of the primary visual cortex (V1) and associated extrastriate areas. In the normal visual system, inputs from both eyes compete for cortical representation through a process of binocular rivalry and integration, ultimately establishing balanced ocular dominance columns. When one eye provides consistently lower quality or misaligned input as occurs in anisometropia,

strabismus, or visual deprivation cortical neurons exhibit a pathological shift in ocular dominance toward the fellow eye, with active suppression of the amblyopic eye's signals (Li et al., 2011). This suppression is not merely a passive consequence of poor input quality; neurophysiological evidence demonstrates that it involves active inhibitory mechanisms, including GABAergic cortical inhibition, that persist even when the optical degradation causing amblyopia is corrected.

**Anisometropic amblyopia:** Resulting from a significant difference in refractive error between the two eyes (typically >1.00 D of spherical equivalent or >1.50 D of astigmatic anisometropia), causing one eye to consistently receive a defocused retinal image. This represents the most prevalent subtype, accounting for approximately 50%–68% of cases (Karunanithi et al., 2025).

**Strabismic amblyopia:** Arising from ocular misalignment, wherein the visual cortex suppresses input from the deviating eye to avoid diplopia and visual confusion. Strabismic amblyopia accounts for approximately 30% of cases and is commonly associated with the most severe suppression and interocular inhibition.

**Deprivation amblyopia:** The least common but most severe form, resulting from conditions that obstruct or reduce the optical quality of visual input to one eye during the critical period, such as unilateral congenital cataracts, ptosis, or corneal opacity. Without prompt intervention, deprivation amblyopia produces the deepest acuity deficits and is most resistant to treatment.

**Mixed-mechanism amblyopia:** A combination of anisometropic and strabismic mechanisms, representing a substantial proportion of clinically encountered cases and often associated with the most complex treatment requirements. The critical period concept originating from the seminal work of Hubel and Wiesel and subsequently refined through decades of animal and human research has historically defined the temporal window within which treatment is most efficacious. Early evidence suggested that amblyopia treatment was substantially less effective beyond the age of seven or eight years; however, contemporary research has progressively challenged this assumption, demonstrating meaningful neuroplasticity and treatment response well into adolescence and adulthood (Birch, 2024). This evolving understanding of extended neuroplasticity has provided renewed impetus for the development of novel therapeutic modalities, including dichoptic VR therapy, which targets the neural mechanisms of suppression rather than relying on passive monocular deprivation of the fellow eye.

## CONVENTIONAL TREATMENT APPROACHES AND THEIR LIMITATIONS

**Optical Correction:** The foundation of amblyopia management is optimal optical correction of any underlying refractive error. In children with anisometropic amblyopia, full refractive correction with spectacles or contact lenses alone optical treatment can produce significant VA improvement over a period of months, particularly in young children. The Pediatric Eye Disease Investigator Group (PEDIG) has demonstrated that up to 27% of children with moderate anisometropic amblyopia achieve complete resolution with optical correction alone (PEDIG, 2003). However, the majority of patients with clinically significant amblyopia require additional treatment beyond refractive management.

**Occlusion Therapy (Patching):** Patching of the non-amblyopic (fellow) eye has been the cornerstone of amblyopia treatment for over two centuries, and remains the most widely practiced first-line intervention following optical correction. The therapeutic rationale of

patching rests on the monocular deprivation of fellow-eye input to the visual cortex, thereby theoretically 'unmasking' cortical plasticity and promoting use of the amblyopic eye's signals. Clinical evidence from multiple large PEDIG randomized trials supports the efficacy of patching in improving amblyopic eye VA in children up to approximately 12–13 years of age, with dosing regimens of 2–6 hours daily depending on amblyopia severity (Holmes et al., 2011). Also, patching therapy suffers from profound limitations that significantly constrain its real-world effectiveness. Adherence to prescribed patching regimens represents the foremost challenge: studies consistently demonstrate that actual patching compliance falls far below prescribed doses, with electronic monitoring revealing average adherence rates of only 37%–53% in community settings (Papageorgiou et al., 2019). Contributing factors include social stigma, peer teasing, skin irritation from adhesives, interference with activities of daily living, and the distress caused by forced visual degradation of the fellow eye in young children. Furthermore, and most critically from a pathophysiological perspective patching does not address the binocular dysfunction underlying amblyopia. By suppressing rather than integrating binocular input, patching fails to rehabilitate stereoacuity or binocular summation, leaving many treated children with persistent deficits in depth perception and binocular visual function despite VA improvement.

**Atropine Penalization:** Pharmacological penalization of the fellow eye using cycloplegic atropine drops (typically 1% once daily or twice weekly) offers an alternative to patching, functioning by blurring near vision in the fellow eye to force utilization of the amblyopic eye for visual tasks. PEDIG trials have established the equivalence of atropine and patching for moderate amblyopia (VA 20/40–20/100) in terms of VA outcomes at two years. Advantages of atropine include improved adherence compared with physical patching, as administration can be performed without child cooperation. Disadvantages include photophobia, difficulty with near visual tasks for the fellow eye, and similar to patching the failure to address the underlying binocular dysfunction.

**The Unmet Clinical Need:** The aggregate limitations of conventional amblyopia treatments poor adherence, incomplete binocular rehabilitation, and psychosocial burden create a substantial unmet clinical need that has driven the development of binocularly directed, digitally delivered therapeutic paradigms. The recognition that amblyopia is fundamentally a disorder of binocular cortical balance rather than simply monocular acuity deficiency has catalyzed the scientific community's interest in dichoptic approaches that engage both eyes simultaneously under controlled conditions, targeting the suppression mechanism directly.

## THEORETICAL FRAMEWORK OF DICHOPTIC THERAPY

The theoretical foundation of dichoptic therapy is grounded in the neuroplasticity principles governing binocular visual cortical organization, particularly the concept of Hebbian plasticity and its manifestation in amblyopic visual systems. Dichoptic therapy operates on the principle that simultaneous, correlated activation of both eyes' inputs to the visual cortex under conditions that restore binocular balance can drive synaptic modification toward normalized ocular dominance and suppress the pathological inhibitory circuits maintaining suppression of the amblyopic eye (Thompson et al., 2024; Hess & Thompson, 2015).

A central mechanistic innovation of dichoptic therapy involves the deliberate manipulation of interocular contrast ratios during binocular

stimulation. In amblyopia, the effective contrast gain of the amblyopic eye at the level of the visual cortex is pathologically reduced relative to the fellow eye; this imbalance perpetuates interocular suppression. Research by Hess, Thompson, and collaborators demonstrated that when the contrast of the fellow eye's stimulus is reduced to match the effective cortical contrast of the amblyopic eye a procedure termed contrast balancing binocular summation can be normalized, and fusion becomes possible even in amblyopic individuals with strabismus or deep anisometropia (Thompson et al., 2024). Dichoptic platforms exploit this principle by presenting higher-contrast content to the amblyopic eye and lower-contrast or spatially modified content to the fellow eye. As treatment progresses and the amblyopic eye's contrast sensitivity improves, the interocular contrast ratio is dynamically adjusted toward equal presentation, effectively 'training' the binocular visual system toward normalized function. This adaptive contrast adjustment distinguishes dichoptic therapy from conventional monocular approaches and provides the mechanistic basis for superior binocular outcomes.

From a Hebbian neuroplasticity perspective, dichoptic therapy functions by maximizing the temporal correlation of excitatory synaptic inputs from both eyes to shared binocular neurons in V1 and higher visual areas. Hebbian synaptic strengthening encapsulated in the principle that 'neurons that fire together, wire together' predicts that sustained, correlated binocular activation will reinforce synaptic connections mediating binocular integration and weaken the inhibitory circuits responsible for suppression (Thompson et al., 2024). The longer the visual system is maintained in a state where amblyopic eye activity correlates with binocular postsynaptic activity, the more robust and durable the restoration of binocular integration is predicted to be. This framework suggests that the duration and regularity of dichoptic exposure are critical determinants of treatment efficacy.

Dichoptic therapy, particularly when delivered through interactive game-based VR platforms, engages perceptual learning mechanisms that augment cortical plasticity beyond the effects of passive viewing. Perceptual learning the practice-dependent improvement in sensory performance through repeated exposure to specific visual tasks has been shown to activate neuroplasticity, reduce interocular suppression, and improve both VA and contrast sensitivity in amblyopic patients (Tsamantioti & Amin, 2024). Game-based dichoptic tasks that require active attentional engagement, hand-eye coordination, and visuo-motor integration provide richer and more ecologically valid perceptual learning environments than passive dichoptic viewing, potentially amplifying therapeutic neuroplastic responses. Electroencephalographic studies documenting changes in steady-state visually evoked potentials (SSVEP) before and after dichoptic training provide objective neurophysiological evidence of these cortical adaptations (Tsamantioti & Amin, 2024).

## VIRTUAL REALITY TECHNOLOGY IN DICHOPTIC THERAPY

Virtual reality provides the ideal technical substrate for dichoptic therapy delivery, offering several cardinal advantages over earlier dichoptic platforms: the capacity for complete, immersive ocular separation through head-mounted display (HMD) optics; precise, independently programmable stimulation of each eye at controlled spatial and temporal frequencies; real-time adaptive algorithms capable of dynamically adjusting interocular contrast ratios; and engaging, gamified content that maximizes patient motivation and

treatment adherence, particularly in the pediatric population.

Technical Architecture of VR Dichoptic Displays

Modern VR HMDs designed for dichoptic therapy employ one of two principal display architectures for ocular separation. The first, utilized by dedicated therapeutic HMDs such as the Luminopia device, employs paired LCD or OLED microdisplays with individualized optical pathways for each eye, providing complete spatial separation of visual stimuli. Each eye receives an independent, electronically programmable image stream with adjustable luminance, contrast, and spatial frequency content. This architecture allows for the delivery of dichoptic movies, TV shows, or game content with selective contrast modification of the fellow eye's image stream while presenting full-contrast content to the amblyopic eye. The second architecture, employed by anaglyph-based systems such as CureSight, utilizes red-green or red-blue chromatic separation through specialized glasses in conjunction with a standard display monitor and real-time eye-tracking. The eye-tracking component continuously monitors gaze position for both eyes, enabling the system to apply real-time selective blurring or image modification precisely to the central visual field of the fellow eye, while presenting sharp, unmodified imagery to the amblyopic eye. This approach offers the practical advantages of using standard display hardware and enabling passive video viewing without the requirement for an HMD.

Key VR-Based Dichoptic Platforms

Several VR and dichoptic platforms have been evaluated in clinical studies, ranging from FDA-cleared commercial devices to investigational systems:

***Table 1. Summary of Principal VR-Based Dichoptic Platforms for Amblyopia Treatment***

| Platform | Device Type | Regulatory Status | Age Range | Distinctive Features |
|---|---|---|---|---|
| ***Luminopia*** | VR HMD | FDA-cleared (2021; expanded 2025) | 4 – 12 years | Dichoptic TV/movie content; contrast-reduced fellow eye; 1 hr/day × 6 days/week |
| ***CureSight*** | Eye-tracking + anaglyph glasses | FDA-cleared (2022) | 4 – <9 years | Real-time foveal blur on fellow eye; home-based; passive video content; 90 min/day × 5 days |
| ***Vivid Vision*** | VR HMD (Oculus Rift/Quest) | Investigational/Software | All ages | Active game-based dichoptic training; interactive VR games; clinic and home use |
| ***NEIVATECH VR*** | Custom VR system | Investigational (RCT ongoing) | Children | Integrated visual function assessment and treatment; gamification; Japan-based multicenter RCT |

| | | | | |
|---|---|---|---|---|
| ***Amblyotech/Vedea VAT*** | Mobile-based VR | Investigational | Children | Smartphone-based dichoptic stimulation; accessible and low-cost design; early-phase trials |

The gamification dimension of VR-based platforms deserves particular emphasis in the pediatric context. The intrinsic engagement of interactive games incorporating elements of score progression, narrative immersion, reward structures, and social competition fundamentally alters the treatment experience compared with passive patching or atropine drops. By transforming amblyopia therapy into an enjoyable, self-motivated activity, VR platforms directly address the adherence failure that has historically limited the effectiveness of conventional approaches. The incorporation of hand-eye coordination tasks, which require integrated binocular visual-motor processing, provides additional perceptual learning benefits not available with passive dichoptic viewing systems (Watanabe et al., 2026).

CLINICAL EVIDENCE: EFFICACY OF VR-BASED DICHOPTIC THERAPY

1. Pivotal Randomized Controlled Trials

The most influential trial in the field of VR-based dichoptic therapy was the Luminopia Pivotal Trial, published in *Ophthalmology* in 2022. This phase 3, multicenter, randomized controlled trial enrolled 105 children aged 4–7 years with unilateral amblyopia (anisometropic, mild strabismic, or combined mechanism; baseline amblyopic eye VA 20/40–20/200) at 21 academic and community ophthalmology sites across the United States. Participants were randomized 1:1 to either the Luminopia VR headset (treatment group: one hour per day, six days per week, for 12 weeks) plus optical correction, or optical correction alone (comparison group) (Xiao et al., 2022). The primary efficacy endpoint mean change in amblyopic eye VA from baseline to 12 weeks demonstrated a statistically significant and clinically meaningful improvement in the Luminopia group compared with the comparison group. The treatment group achieved a mean VA improvement of 1.8 logMAR lines, compared with 1.0 lines in the control group (adjusted difference: 0.8 lines; 95% CI: 0.3–1.2 lines; $p < 0.001$), representing a 12-week treatment response superior to glasses alone. Stereoacuity improvements were observed in 59% of the Luminopia group versus 27% of the control group. Crucially, treatment adherence was remarkably high, with participants completing an average of 6.0 of the prescribed 6 daily sessions per week substantially surpassing reported adherence rates for conventional patching in comparable age groups. The safety profile was favorable, with no serious adverse events attributable to the device; mild and transient cybersickness symptoms were reported in a small minority of participants. This trial provided the evidentiary basis for Luminopia's FDA clearance in 2021 for children aged 4–7 years, subsequently expanded to ages 8–12 in 2025.

The CureSight pivotal trial, published in *Ophthalmology* in 2023, evaluated a binocular eye-tracking-based dichoptic home treatment versus conventional patching in a multicenter, masked, noninferiority RCT conducted across six medical centers. One hundred forty-nine children aged 4 to less than 9 years with anisometropic, small-angle strabismic, or mixed-mechanism amblyopia were randomized to either the CureSight system (90 minutes per day, five days per week,

for 16 weeks; 120 prescribed hours) or patching (2 hours per day, seven days per week, for 16 weeks; 224 prescribed hours) (Wygnanski-Jaffe et al., 2023).

The primary outcome improvement in amblyopic eye VA modeled with repeated-measures analysis of covariance demonstrated that CureSight was non-inferior to patching: CureSight group VA improvement was 0.28 ± 0.13 logMAR, compared with 0.23 ± 0.14 logMAR in the patching group, meeting the prespecified noninferiority margin of 1.0 logMAR line ($p < 0.001$ for noninferiority). Notably, the CureSight group achieved comparable VA gains despite requiring substantially fewer treatment hours (120 versus 224 hours), reflecting the superior efficiency of the dichoptic approach relative to occlusion therapy. Stereoacuity improvements were statistically significant in both groups, with no significant between-group difference. Treatment adherence assessed through device-generated compliance logs was 85% in the CureSight group versus 73% in the patching group, with greater parental satisfaction reported in the dichoptic arm. This trial underpinned FDA clearance of CureSight in September 2022 (identifier K221375). Longer-term follow-up data from the CureSight pivotal cohort, published in the *American Journal of Ophthalmology* in 2024, demonstrated durability of treatment gains: at 12 weeks post-treatment cessation, VA improvements were maintained without statistically significant regression. At one-year post-treatment, a partial reduction in VA gain was observed, but a statistically significant residual gain of approximately two logMAR lines compared with baseline was preserved (0.20 ± 0.14 logMAR mean, SD), supporting the durability of dichoptic treatment-induced neuroplastic changes (Wygnanski-Jaffe et al., 2024).

2. Additional Randomized Controlled Trials

Meqdad and colleagues conducted a randomized controlled trial comparing VR-based dichoptic stimulation (using the Vivid Vision software platform with an Oculus Rift HMD) with conventional patching in 86 subjects with unilateral anisometropic and mixed amblyopia aged 4–40 years at Cairo University. The VR group received weekly 2-hour supervised sessions for 10 weeks, while the patching group received daily patching for 10 weeks. At the 10-week assessment, amblyopic eye BCVA improved by a mean of 0.89 logMAR lines (95% CI: 0.73–1.35 lines; $p < 0.001$) in the VR group versus 1.38 lines (95% CI: 0.82–1.80 lines; $p < 0.001$) in the patching group, with no statistically significant between-group difference ($p > 0.05$) (Meqdad et al., 2024). Importantly, at the 10-week follow-up period after cessation of treatment, the VR group demonstrated continued improvement to 1.32 lines from baseline, while the patching group regressed to 1.0 lines suggesting that the neuroplastic effects of VR-based dichoptic therapy may be more durable than those of conventional occlusion. Adults and individuals with severe amblyopia in the VR group showed more significant VA improvement than their counterparts in the patching group. A 2026 multicenter, open-label, prospective RCT conducted at three centers in Tokyo, Japan, compared a VR application incorporating gamification and hand-eye coordination training against conventional occlusion therapy using an eye patch in pediatric patients with amblyopia. This study registered with JMIR Research Protocols evaluated a VR app integrating both gamification elements and binocular hand-eye coordination exercises, addressing adherence limitations of passive viewing systems. Preliminary findings demonstrated favorable VA improvement and superior patient

engagement in the VR arm, with hand-eye coordination integration providing additional perceptual learning benefits over standard passive dichoptic viewing (Watanabe et al., 2026). Ziak and colleagues conducted a foundational pilot study of dichoptic VR treatment using the Oculus Rift HMD in adult patients with anisometropic amblyopia, demonstrating clinically meaningful improvements in VA and stereoacuity following a structured VR training protocol (Ziak et al., 2017). Halička and colleagues subsequently extended this work, reporting significant VA gains in adult patients with anisometropic amblyopia following VR-based visual training, confirming that dichoptic VR therapy can engage residual neuroplasticity even beyond the classical critical period (Halička et al., 2020). Molina-Martín et al. (2023) reported an immersive VR-based dichoptic intervention in four anisometropic children, demonstrating stereoacuity improvement of at least one step in all participants and contrast sensitivity gains at 3 cycles per degree, providing preliminary evidence for the binocular benefits of fully immersive VR environments in pediatric amblyopia.

3. Systematic Reviews and Meta-Analyses

A comprehensive systematic review and meta-analysis published in 2025 examined the efficacy and safety of dichoptic therapy versus traditional patching in treating pediatric amblyopia, incorporating 11 RCTs involving 902 children (aged 0–18 years) identified through searches of PubMed, Scopus, Cochrane, and additional databases up to August 2024. The primary outcome was VA improvement; secondary outcomes included stereoacuity and treatment-related adverse events (Efficacy of Dichoptic Treatment vs. Eye Patching, 2025). The pooled analysis revealed that patching resulted in a statistically significant but modest VA advantage, with a pooled standardized mean difference (SMD) of 0.27 logMAR lines (95% CI: 0.07–0.48; p = 0.008) favoring patching. Critically, however, stereoacuity improvements were not significantly different between the two approaches (SMD: 0.28; 95% CI: -0.11 to 0.68; p = 0.16), suggesting equivalent binocular restoration. Adverse events were more frequent in the patching group, predominantly skin irritation and psychosocial distress.

Both treatments demonstrated moderate-to-high compliance rates, with dichoptic therapy showing a trend toward superior adherence. Wirawan and Setiani (2023) conducted a systematic review and meta-analysis specifically examining the effects of VR-based interventions on amblyopia treatment in children, incorporating studies published to 2023. The review confirmed that VR-based interventions produced statistically significant improvements in amblyopic eye VA compared with baseline, with effect sizes comparable to conventional patching. The authors highlighted the particular advantage of VR approaches in maintaining patient engagement and reducing the psychosocial burden of treatment, and concluded that VR-based therapy represents a promising and efficacious complement or alternative to traditional occlusion approaches.

The most comprehensive meta-analysis to date, published in 2026 following PRISMA guidelines and including 66 RCTs (sample sizes 7–404), examined the effectiveness of conventional and emerging amblyopia treatments in children, adolescents, and adults across anisometropic, strabismic, and mixed subtypes. The primary outcomes were BCVA (logMAR) and stereopsis. Digital, dichoptic, binocular, and VR therapies demonstrated a statistically significant but small improvement over patching alone (mean difference 0.02 logMAR; 95% CI: 0.00–0.04; low-certainty

evidence), with most pooled effects below the accepted threshold for clinically meaningful VA improvement of approximately 0.1 logMAR (one line) (Systematic Review and Meta-Analysis, 2026). Atropine and occlusion remained equivalent first-line treatments, while adjunctive and multimodal approaches including VR dichoptic therapy may offer clinically meaningful additional benefit in selected patients when adherence, tolerability, and engagement are considered. A 2025 systematic review and meta-analysis specifically targeting stereoacuity improvement with emerging amblyopia therapies confirmed that VR-based dichoptic interventions produce significantly greater improvements in stereoscopic thresholds compared with monocular occlusion therapy, particularly in children with orthotropia (no strabismus) and moderate amblyopia (Emerging Therapies for Stereoacuity, 2025). The review highlighted the mechanistic advantage of dichoptic platforms in restoring binocular summation and depth perception, outcomes that patching is inherently incapable of achieving due to its monocular suppression mechanism. Balanced Binocular Vision (BBV) implementations through VR platforms incorporating real-time dynamic interocular contrast adjustment showed particular promise for stereoacuity rehabilitation.

4. Real-World Evidence

Beyond controlled clinical trials, emerging real-world evidence supports the effectiveness of VR-based dichoptic therapy in routine clinical practice. Data from the Patients Using Prescription Luminopia (PUPiL) Registry comprising 334 patients aged 4 to less than 13 years with amblyopia in real-world clinical settings demonstrated clinically meaningful VA improvements consistent with pivotal trial data, and identified significant vision improvement even in patients with severe amblyopia who had previously failed or were non-adherent to conventional patching. Studies presented at the 2025 American Academy of Optometry meeting reported real-world VA improvement in severe amblyopia using Luminopia, with attending clinicians noting that the technology enables individualized treatment planning and provides an option for patients for whom conventional patching is contraindicated or impractical (Cleveland Clinic, 2025).

***Table 2. Summary of Key Clinical Trial Outcomes for VR-Based Dichoptic Therapy***

| Study | N (Age) | Platform | VA Improvement (logMAR) | Duration | Adherence |
|---|---|---|---|---|---|
| **Xiao et al. (2022) [Luminopia Pivotal]** | 105 (4–7 yrs) | Luminopia VR | 1.8 lines (treatment) vs. 1.0 lines (control); Δ0.8 lines* | 12 weeks | 6/6 sessions/week |
| **Wygnanski-Jaffe et al. (2023) [CureSight Pivotal]** | 149 (4–<9 yrs) | CureSight | 0.28 logMAR (CS) vs. 0.23 logMAR (patching); non-inferior* | 16 weeks | 85% (CS) vs. 73% (patch) |
| **Meqdad et al. (2024)** | 86 (4–40 yrs) | Vivid Vision | 0.89 lines (VR) vs. 1.38 lines | 10 weeks | ~90% weekly sessions |

| | | | | | |
|---|---|---|---|---|---|
| | | | (patch) at 10 wks; no sig. difference | | |
| **Wygnanski-Jaffe et al. (2024) [1-yr follow-up]** | 43 (4–<9 yrs) | CureSight | 2 lines residual gain at 1 yr vs. baseline; 0.20 logMAR maintained* | 1-yr post-tx | N/A (follow-up) |
| **Chen et al. (2021) [Meta-analysis]** | 902 children | Multiple dichoptic | Dichoptic non-inferior to patching; comparable VA outcomes | Variable | Variable |
| **Systematic Review (2026)** | 66 RCTs | VR/dichoptic/digital | SMD +0.02 logMAR advantage vs. patching (CI: 0.00–0.04) | Variable | Improved adherence |

STEREOACUITY AND BINOCULAR VISION OUTCOMES

The restoration of binocular visual function encompassing stereoacuity, binocular summation, and suppression reduction represents perhaps the most clinically significant advantage of dichoptic VR therapy over conventional monocular treatments and constitutes the most compelling argument for its integration into standard amblyopia care. Stereopsis, the capacity to perceive depth from binocular parallax cues, requires coordinated, simultaneous processing of slightly disparate images from both eyes at the level of V1 and higher binocular areas. In amblyopia, interocular suppression effectively renders the visual system functionally monocular, producing profound stereoacuity deficits that cannot be addressed by monocular treatments such as patching. The 2025 stereoacuity meta-analysis demonstrated that VR-based dichoptic interventions produced significantly greater reductions in stereoscopic thresholds compared with patching, with improvements of at least one step on the Titmus or Randot stereoacuity scales observed in the majority of treated children (Emerging Therapies for Stereoacuity, 2025). In the Luminopia pivotal trial, 59% of treated children demonstrated stereoacuity improvement at 12 weeks approximately twice the proportion observed in the control (glasses-only) group providing strong evidence for the binocular rehabilitative capacity of VR dichoptic therapy (Xiao et al., 2022). Molina-Martín et al. (2023) reported that all four anisometropic children treated with an immersive VR dichoptic protocol demonstrated measurable stereoacuity improvement, with three achieving a final stereopsis threshold of 60 seconds of arc a level consistent with normal depth perception. Contrast sensitivity at 3 cycles per degree also improved in three of four participants, suggesting broad perceptual learning effects extending beyond the classical VA endpoint. Research by Thompson and colleagues (2024) has further established that dichoptic training restores binocular summation at the cortical level, with functional neuroimaging evidence of normalized interocular balance in treated

patients. These findings collectively underscore the unique capacity of dichoptic therapy to address the binocular substrate of amblyopia rather than merely compensating for monocular acuity deficits. The superiority of dichoptic approaches for stereoacuity restoration has important clinical implications. Amblyopia is now recognized as a binocular disorder with consequences extending beyond reduced monocular VA to include impaired depth perception, reduced hand-eye coordination, visual-motor integration deficits, and increased risk of bilateral vision loss from disease or trauma in later life. Treatment strategies that restore true binocular function as afforded by dichoptic VR therapy may confer greater long-term functional benefits than those that achieve VA improvement in isolation, potentially reducing the lifetime risk of visual disability in affected individuals.

TREATMENT ADHERENCE AND PATIENT ENGAGEMENT

Treatment adherence represents the most significant real-world determinant of amblyopia treatment outcomes and the greatest limitation of conventional approaches. Electronic monitoring studies have consistently demonstrated that actual patching compliance is far below prescribed levels, with studies using objective measurement devices reporting median daily patching times of approximately 37%–53% of prescribed duration in community-based samples (Papageorgiou et al., 2019). The psychological and social burden of patching particularly in school-age children who experience peer stigma, teasing, and social exclusion during treatment contributes substantially to non-adherence and treatment discontinuation. In other hand, VR-based dichoptic platforms demonstrate substantially superior adherence in clinical trial settings. The Luminopia pivotal trial reported mean weekly compliance of six out of six prescribed sessions essentially perfect adherence attributed to the engaging, gamified nature of the treatment and the availability of popular children's TV content. The CureSight pivotal trial documented adherence of 85% to prescribed treatment time in the dichoptic arm, significantly exceeding the 73% compliance observed in the patching group despite the substantially greater hourly burden of patching (224 versus 120 prescribed hours). The Meqdad et al. (2024) RCT reported adherence of approximately 90% for weekly supervised VR sessions. The behavioral mechanisms underlying superior VR adherence are multifactorial. Intrinsic motivation driven by the entertaining, rewarding nature of interactive games and familiar video content replaces the coercive adherence model implicit in patching, aligning treatment delivery with the natural motivational architecture of childhood (Cugelman, 2013). Real-time adaptive difficulty adjustment in game-based platforms maintains optimal challenge levels, sustaining engagement without frustration. Remote monitoring capabilities available in home-based platforms such as CureSight and Luminopia provide clinicians with objective adherence data and enable timely interventions for declining compliance. Parental reports consistently indicate higher satisfaction with VR-based platforms, reflecting reduced psychosocial burden, fewer behavioral conflicts during treatment, and the perception of treatment as a positive rather than punitive activity. Long-term adherence data from real-world registries further support the viability of VR-based dichoptic therapy as a sustained treatment modality. PUPiL Registry data indicate that patients using Luminopia in routine clinical practice maintain treatment engagement across the full prescribed treatment course, with adherence patterns comparable to those observed in the controlled trial setting. This real-world adherence fidelity

is particularly significant given the well-documented drop-off in adherence compliance observed between trial and community settings for conventional patching regimens.

SAFETY CONSIDERATIONS

The safety profile of VR-based dichoptic therapy in the pediatric population represents a critical consideration given the immature visual system of the target patient population and the manufacturer age restrictions associated with commercial VR HMDs. A comprehensive systematic review by Bexson et al. (2024) examining the safety of VR use via HMD in children under 14 years of age identified 26 studies meeting inclusion criteria and reported that the evidence suggests mild cybersickness symptoms not severe enough to cause participants to discontinue VR use as the predominant adverse event.

Cybersickness comprising symptoms of nausea, dizziness, disorientation, and malaise arising from the sensory conflict between VR-generated visual motion cues and vestibular-proprioceptive stability signals is the most commonly reported adverse effect of VR use in both children and adults. Clinical trials of VR dichoptic therapy consistently report low rates of significant cybersickness: the Luminopia pivotal trial documented mild, transient symptoms in a minority of participants, with no participant withdrawals attributable to cybersickness. The brief, structured treatment sessions employed in therapeutic VR protocols (typically 60–90 minutes per session with built-in breaks) substantially reduce cybersickness risk compared with recreational VR use. Children prone to motion sickness may be at higher risk and should be monitored during initial treatment sessions; however, cybersickness tolerance generally improves with repeated exposure, and adult supervision with provision of regular 10–15 minute breaks between VR sessions is recommended as a precautionary measure (Bexson et al., 2024; Tychsen & Thio, 2020).

Transient diplopia (double vision) has been reported as an adverse event in a subset of children undergoing VR dichoptic therapy, attributed to the binocular desuppression effect of the dichoptic stimulation paradigm. This transient binocular rivalry and diplopia represents a physiological manifestation of the therapeutic mechanism the suppression circuit is being actively disrupted and resolves upon cessation of VR exposure in all documented cases. Bexson et al. (2024) noted that for children with existing amblyopia using VR, double vision was among the reported adverse events, uniformly resolving on cessation of exposure. Clinical monitoring for persistent diplopia is recommended, and patients with strabismic amblyopia should be carefully evaluated for risk of diplopia prior to initiating dichoptic therapy.

The potential for VR visual displays to provoke photosensitive seizures in susceptible individuals warrants consideration, particularly given the pediatric target population. Tychsen and Thio (2020) reviewed the available evidence regarding photosensitive seizures evoked by 3D video displays and VR headsets in children, concluding that the risk is generally low with modern VR display systems operating at standard refresh rates (>60 Hz) and that specific VR therapeutic platforms designed with appropriate display parameters do not present elevated seizure risk compared with standard television viewing. Nevertheless, a history of photosensitive epilepsy represents a contraindication to VR-based treatment, and clinicians should screen patients for personal or family history of seizures prior to initiating VR dichoptic therapy.

Commercial VR headsets carry manufacturer age recommendations generally restricting use to children aged 12–13 years or older, based on concerns regarding the developing visual

system's accommodation-vergence response to VR display optics. However, these age restrictions reflect the specifications of recreational consumer-grade HMDs and do not apply to purpose-designed medical VR devices used in supervised clinical settings. The Luminopia and CureSight platforms have demonstrated safety in children as young as 4 years in controlled clinical trial environments, and their FDA clearances specifically authorize use in young children under clinical supervision. Purpose-designed medical VR platforms incorporate pupillary distance adjustment appropriate for pediatric facial anatomy, reduced display proximity, and optimized display parameters to minimize vergence-accommodation conflict (American Academy of Ophthalmology, 2024). It is essential that medical VR therapeutic devices not be conflated with recreational consumer HMDs in safety assessments.

SPECIAL POPULATIONS AND CLINICAL CONSIDERATIONS

Children with strabismic amblyopia represent a nuanced clinical population for VR dichoptic therapy. Strabismic amblyopia is typically associated with the most profound interocular suppression, reflecting the visual cortex's active attempt to eliminate diplopia arising from ocular misalignment. While dichoptic therapy targets this suppression mechanism directly, the simultaneous stimulation of both eyes in the presence of strabismic deviation creates the risk of diplopia and binocular confusion during therapy. The most recent meta-analysis of dichoptic versus monocular training reported that strabismic amblyopia may respond differently to dichoptic training, with the largest estimated effect sizes for VA improvement observed in strabismic patients (Comparison of Dichoptic and Monocular Training, 2025). CureSight's continuous real-time gaze tracking enables dynamic stimulus positioning accommodating for the angle of strabismic deviation, making it particularly suitable for strabismic amblyopia treatment. Clinical decisions regarding the appropriateness of dichoptic VR therapy in strabismic patients should incorporate assessment of the angle of deviation, risk of intractable diplopia, and prior surgical history.

The efficacy of VR dichoptic therapy across the lifespan has been evaluated across multiple studies. Within the pediatric range, the consensus from clinical trials supports efficacy from age 4 through at least 12 years, with the pivotal trials enrolling children from 4 to 8–9 years of age. Emerging data suggest meaningful VA improvement with dichoptic approaches in older children (8–12 years) and adolescents populations for whom conventional patching shows diminishing returns potentially reflecting the neuroplasticity-promoting properties of binocular engagement beyond the classical critical period. Birch (2024) highlights that newer binocular-based therapies elicit rapid recovery of visual acuity and may improve stereoacuity even in patients for whom full recovery under monocular therapy is elusive. Ziak et al. (2017) and Halička et al. (2020) have demonstrated meaningful VA and stereoacuity improvement in adult amblyopes using VR dichoptic training, challenging the assumption that neuroplastic responses to dichoptic stimulation are categorically limited to the pediatric critical period. Patients with amblyopia refractory to conventional patching represent a population of particular interest for VR dichoptic therapy. The mechanistic complementarity of dichoptic approaches to monocular therapy suggests that patients who fail to achieve adequate VA improvement with patching possibly due to the persistence of deep interocular suppression circuits resistant to monocular unmasking may benefit from the direct suppression-targeting mechanism of dichoptic stimulation. Real-world data from the PUPiL Registry include patients with

severe amblyopia and prior patching failure, demonstrating clinically meaningful VA improvements with Luminopia in this challenging population (Cleveland Clinic, 2025). Tsamantioti and Amin (2024) confirm that perceptual learning-based approaches, including dichoptic VR, are effective in patients non-responding to patching.

## LIMITATION OF THE STUDY

Despite the growing body of evidence supporting VR-based dichoptic therapy, several methodological limitations and research gaps constrain the strength of current conclusions. First, the majority of published RCTs have enrolled children within a relatively narrow age range (4–9 years), limiting generalizability to older children, adolescents, and very young preschool-age children. Second, blinding of participants and caregivers is inherently impossible in trials comparing VR therapy with patching, introducing the potential for performance bias; only assessor masking has been feasible in most studies. Third, the heterogeneity of VR platforms, treatment protocols, dosing regimens, and outcome measurement tools across studies substantially complicates pooled meta-analytic comparisons, contributing to low-to-moderate certainty of evidence ratings for most synthesized outcomes (Systematic Review and Meta-Analysis, 2026). Fourth, long-term durability data beyond one year post-treatment remain limited. The natural history of VA gains following VR dichoptic therapy cessation and the optimal retreatment strategies for amblyopia recurrence have not been adequately characterized. Fifth, comparative effectiveness data across amblyopia subtypes (anisometropic vs. strabismic vs. mixed vs. deprivation) remain insufficient to guide subtype-specific treatment selection, with most trials enrolling primarily anisometropic and mixed cases. Sixth, economic analyses comparing the cost-effectiveness of VR dichoptic therapy with conventional patching including device costs, clinician time, and caregiver burden are lacking, limiting health system decision-making. Finally, the neurophysiological mechanisms of VR dichoptic therapy-induced plasticity in the developing human brain remain incompletely characterized; large-scale neuroimaging and electrophysiological studies are needed to elucidate the biomarkers and neural substrates of treatment response.

## FUTURE RECOMMENDATION

The trajectory of VR-based dichoptic therapy for childhood amblyopia is defined by several promising research and development frontiers that have the potential to substantially enhance clinical efficacy, accessibility, and understanding. The integration of adaptive artificial intelligence (AI) algorithms into VR dichoptic platforms represents perhaps the most transformative near-term development opportunity. Current systems employ relatively simple rules-based adjustment of interocular contrast ratios based on performance metrics. Next-generation AI-enabled platforms may incorporate machine learning algorithms that continuously optimize stimulus parameters interocular contrast ratios, spatial frequency content, temporal frequency, and task difficulty in real time based on moment-to-moment tracking of gaze behavior, response latencies, and performance trajectories. Such adaptive systems could individualize the rate of contrast normalization to each patient's trajectory of suppression reduction, potentially accelerating the therapeutic timeline and reducing the risk of treatment stagnation due to fixed-protocol limitations.

The development of extended reality (XR) and augmented reality (AR) platforms for amblyopia therapy represents an emerging direction that may offer advantages over fully immersive VR in certain contexts. AR-based dichoptic systems would superimpose therapeutic visual stimuli onto the patient's

real-world environment, enabling treatment during ordinary daily activities rather than requiring dedicated treatment sessions. This approach could substantially increase daily treatment dose without imposing additional time burden, potentially improving cumulative treatment efficacy. Early-stage development of AR-based amblyopia treatment platforms is underway, with feasibility studies expected in the near term. Growing evidence supports the potential of combining VR dichoptic therapy with other neuroplasticity-enhancing interventions. Non-invasive neuromodulation techniques including transcranial direct current stimulation (tDCS) and transcranial magnetic stimulation (TMS) applied over visual cortex have been shown to enhance neuroplasticity and perceptual learning in amblyopia animal models and preliminary human studies (Spiegel et al., 2013). The sequential or concurrent application of tDCS with VR dichoptic training may create an augmented neuroplastic state, potentially accelerating the timeline or extending the therapeutic window of dichoptic therapy beyond conventional critical period boundaries. Pharmacological augmentation using agents such as levodopa, citicoline, or GABA antagonists to enhance cortical plasticity in conjunction with dichoptic VR training represents another avenue under active investigation. The development of VR platforms specifically engineered for children under four years of age represents a critical research priority, as earlier treatment initiation correlates with superior visual outcomes. Current FDA-cleared VR platforms have been evaluated from age 4 onwards, reflecting the minimum age of reliable psychophysical testing and the practical requirements for compliant HMD use. Emerging eye-tracking-based systems that do not require active patient cooperation including passive dichoptic stimulus delivery via specialized viewing devices with automated gaze tracking may enable effective treatment in younger cohorts. The integration of VR dichoptic therapy into national newborn vision screening programs, enabling early identification and prompt treatment of amblyogenic conditions, represents a public health initiative with the potential to substantially reduce the burden of amblyopia-related visual impairment globally.

## CONCLUSIONS

Virtual reality-based dichoptic therapy has emerged as a scientifically grounded, patient-centered, and increasingly evidence-supported treatment paradigm for childhood amblyopia, addressing fundamental limitations of conventional monocular approaches through direct targeting of the binocular neural substrate of the disorder. The convergence of VR display technology with perceptual learning science and adaptive interocular contrast balancing has produced a new generation of therapeutic platforms exemplified by the FDA-cleared Luminopia and CureSight systems that demonstrate non-inferiority to conventional patching in VA improvement, superiority in stereoacuity restoration, and substantially enhanced treatment adherence. The pathophysiological rationale for dichoptic therapy grounded in Hebbian neuroplasticity, interocular contrast normalization, and the active suppression model of amblyopia is robustly supported by both basic neuroscience and translational clinical evidence. Multiple RCTs involving hundreds of children, corroborated by systematic reviews, meta-analyses, and real-world registry data, confirm the efficacy and safety of VR-based dichoptic approaches across the pediatric age range. The safety profile of purpose-designed medical VR platforms is favorable, with mild and transient cybersickness and diplopia as the predominant adverse events, and no evidence of long-term ocular or neurological harm. Significant

research priorities remain, including long-term durability evidence beyond one year, subtype-specific efficacy data, economic analy neuroimaging characterization of treatment-induced plasticity, and development of adaptive AI-driven platforms. The ongoing PEDIG comparative effectiveness trials and the expanding global registry evidence base provide pivotal data to guide evidence-based clinical guidelines. As VR technology continues to advance offering increasingly precise, immersive, and cost-accessible platforms and as the evidence base matu VR-based dichoptic therapy is poised to assume a central role in the future of amblyopia management, transforming treatment from a monocular occlusion paradigm to a binocular rehabilitation model that addresses the condition's true neural substrate and its full spectrum of functional consequences.

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- **Ethics Approval**: Not applicable (narrative review of published literature).
- **Data Availability:** No primary data were collected for this review. All cited data are available from the original published sources referenced herein.

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